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NUMERICAL PREDICTION OF HEAD/NECK RESPONSE TO SHOCK-IMPACT, (U)

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NUMERICAL PREDICTION OF HEAD/NECK RESPONSE TO SHOCK-IMPACT

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ABSTRACT

A three-dimensional, 54 degree of freedom computer model of the head/neck system is presented. The model consists of a series of rigid bodies representing the bones and vertebrae together with springs and dampers representing the muscles, discs, ligaments, and joints. Equations of motion are written for the model by using Lagrange's form of d'Alembert's principle. Computer algorithms are developed to numerically calculate the coefficients of these equations. The governing equations are then integrated numerically for a number of specific cases. The results agree very well with experimental data

NOMENCLATURE

- A = Disc area
- C, C₁, C₂ = Joint damping constants
- d₁, d₂ = Disc constants
- e_{ij} = Standard permutation symbol
- k_{ij} = Elastic constant
- F = Disc, ligament, muscle, or joint force
- F_i = Generalized force associated with X_i
- G = Shear modulus
- h = Disc height
- I = Second centroidal moment of area
- I_{kij} = Centroidal inertia matrix of the kth body of the system
- J_{kij} = Polar moment of area
- k = Shape factor
- L₁, L₂ = Ligament constants
- m₁, m₂ = Muscle constants
- m_k = Mass of the kth body of the system
- n_i = Unit of Vectors fixed in R
- R = Inertial reference frame

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v_{ijk} = Partial rate of change of position
 x_i = Generalized coordinates
 X = Forward direction
 Y = Left direction
 Z = Axial (up) direction
 δ = Displacement
 θ = Rotation
 ω_{ijk} = Partial rate of change of orientation

INTRODUCTION

The recent research efforts in biomechanics and biomedical engineering have fostered a growing interest in head/neck biodynamic models. This interest has been stimulated by the awareness that 60-70% of vehicle related fatalities are caused or involve injuries to the head or neck. To date, a satisfactory, comprehensive head-neck model has not been developed which accounts for all the degrees of freedom and which possesses all the neuro-muscular responses. There have, however, been a number of excellent models discussed in the literature. Specifically, in 1971, Orne and Liu [1] developed a discrete-parameter spine model which simultaneously accounts for axial, shear, and bending deformation of the discs, for the variable size and mass of the vertebrae and discs, and for the natural curvature of the spine. They also present an extensive literature review of the spine models prior to 1970. Later in 1971, McKenzie and Williams [2] used the Orne-Liu model to develop a two-dimensional discrete parameter head-neck-torso model for "whiplash" investigation. A two-dimensional mechanical linkage model simulating head-neck response to frontal impact has been presented by Becker [3]. This model allows for elongation of the neck. It concentrates the mass at the head mass center. Springs and dampers are used to control the elongation of the model. A three-dimensional neck-torso linkage vehicle-occupant model has been developed by Bowman and Robbins [4]. The model has two ball-and-socket joints and the neck can elongate with the motion limited by joint stopping moments.

In addition to these computer models there have also been developed a number of wholebody, anthropometric dummy models. (These are currently used extensively by the automotive industry). In 1972, Melvin, et al. [5] presented a mechanical neck for anthropometric dummies. The neck consists of three steel universal joints pinned into aluminum discs with shaped rubber discs around the joints. The joints allow the neck to move in flexion, extension, and lateral flexion but do not allow for either rotation or elongation. A mechanical neck has also been presented by Culver, et al. [6]. It consists of four ball-joint segments and one pin-connected "nodding" segment. Viscoelastic resistive elements inserted between the segments provide for bending resistance and energy dissipation with the primary objective being to model flexion and extension responses.

In this paper, there is presented a comprehensive, three-dimensional head-neck computer model which has 54 degrees of freedom and includes the effects of the discs, muscles and ligaments. The model is based primarily on the research of J. Huston and Advani [7, 8, 9] which in turn uses the principles of the whole-body simulation of R. Huston, Passerello, et al. [10, 11, 12]

The balance of the paper is divided into four parts with the first part providing some preliminary background on the head-neck anatomy, geometry, and modelling. The next part presents a summary of the development of the equations of motion and the computer algorithms of the head-neck model. The third part presents a comparison of numerical results, predicted by the model, with experimental data. The final part contains a brief discussion and some conclusions.

HEAD-NECK ANATOMY AND MODELLING

A comprehensive presentation of the head-neck anatomy may be found in references [13-20]. The anatomy is conveniently divided into two categories: bones and soft tissue.

Bones

The largest and heaviest bone is the skull which consists of a large cranial cavity (enclosing the brain) and smaller bones containing the face and jaw. The skull is actually composed of 21 closely fitted bones. The other bones of the head-neck system are seven cervical vertebrae (C1-C7) which support and provide mobility of the head. The first of these C1, called the "atlas", supports the skull. The second C2, called the "axis", is distinctive because of its odontoid process (or axis) which rises perpendicularly to the vertebrae. The five remaining cervical vertebrae are roughly annular in shape and are similar to each other with a slight increase in size going down from C3 to C7.

Soft Tissue

The soft tissue is composed primarily of the discs, the muscles, the ligaments and the brain. The discs provide the cushioning or separation for the vertebrae. They are annular in shape. The ligaments connect the cervical vertebrae to each other and thus allow for the gross and fine movement of the head and neck. The movements of the head and neck, which may be classified grossly as flexion, extension and rotation, are controlled by the muscles. The muscles originate on the various cervical vertebrae, the skull, the spine and the shoulder bones. The brain tissue is basically four mass volumes composed of two cerebral hemispheres in the upper half of the skull, the triangular shaped cerebellum in the lower posterior and the brain stem in the center of the skull.

Modelling

The head-neck system is modelled by a system of 9 rigid bodies representing the skull, vertebrae and torso, as shown in Figure 1, and springs and dampers representing the discs, ligaments and muscles. The masses, inertia matrices, and overall geometry of the rigid bodies are adjusted to match the actual human values [7]. Each body has 6 degrees of freedom and hence the entire system has a total of 54 degrees of freedom.

Following Orne and Liu [1], the discs are modelled in the axial direction as two-parameter viscoelastic solids with the uniaxial force-displacement relationship being:

$$F = (A/h) (d_1 \delta + d_2 \dot{\delta}) \quad (1)$$

In bending and shear the discs are modelled as linear elastic solids. Using the principles of strength of materials theory [7], the following force and moment equations are developed:

$$F_x = \left(\frac{6EI_1}{h^2} \right) \left(\frac{2\delta_x}{h} - \theta_y \right) / P_1 \quad (2)$$

$$F_y = \left(\frac{6EI_2}{h^2}\right) \left(\frac{2\delta_y}{h} + \theta_x\right) / P_2 \quad (3)$$

$$F_z = \left(\frac{A}{h}\right) (d_1 \delta_z + d_2 \delta_z) \quad (4)$$

$$M_x = \left(\frac{EI_2}{hP_2}\right) \left[\frac{6\delta_y}{h} + (P_2 + 3) \theta_x\right] \quad (5)$$

$$M_y = \left(\frac{EI_1}{hP_1}\right) \left[\frac{-6\delta_x}{h} + (P_1 + 3) \theta_y\right] \quad (6)$$

$$M_z = JG\theta_z/h \quad (7)$$

where P_1 and P_2 are:

$$P_1 = 1 + \frac{12EI_1 k_x}{GAh^2} \quad (8)$$

and

$$P_2 = 1 + \frac{12EI_1 k_y}{GAh^2} \quad (9)$$

where as shown in Figure 1, Z is in the axial (up) direction, X is forward and Y is to the left.

The ligaments are modelled as non-linear elastic bands capable of exerting force only in tension. The force-displacement relation is taken as:

$$F = k_1 \delta + k_2 \delta^2 \quad (10)$$

The muscles are modelled as two parameter, visco-elastic solids, which like the ligaments, only exert force when in tension. The force-displacement relation is taken as:

$$F = m_1 \dot{\delta} + m_2 \ddot{\delta} \quad (11)$$

The joint constraints (limiting the relative motion of the bodies) are modelled as one-way dampers. The force-displacement and moment-rotation relations are taken as:

$$F = \begin{cases} -C\dot{\delta} & \text{for } \dot{\delta} > 0 \\ 0 & \text{for } \dot{\delta} < 0 \end{cases}$$

and

$$M = \begin{cases} -C\dot{\theta} & \text{for } \dot{\theta} > 0 \\ 0 & \text{for } \dot{\theta} < 0 \end{cases} \quad (12)$$

where the damping constant is

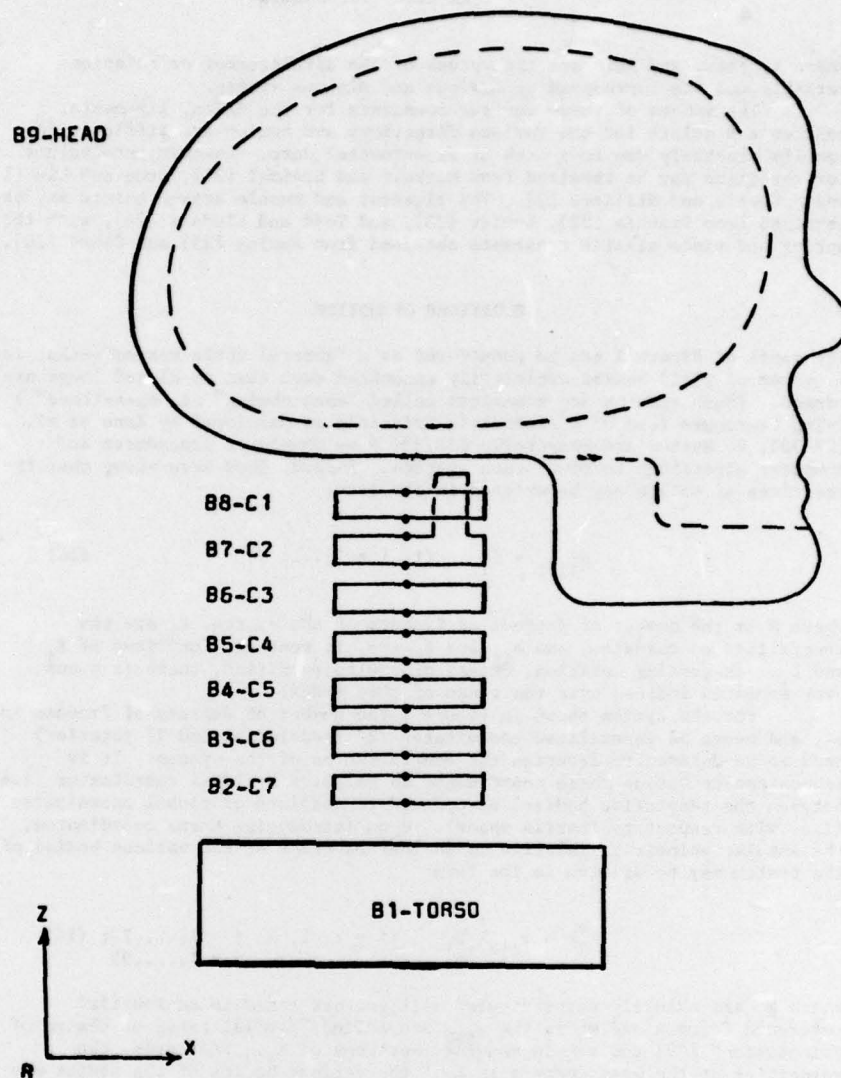


Fig. 1 The head-neck model

$$C = \begin{cases} C_0 + C_1(X - X_{\max}) & \text{for } X > X_{\max} \\ C_0 & \text{for } X_{\min} < X < X_{\max} \\ C_0 + C_1(X - X_{\min}) & \text{for } X < X_{\min} \end{cases} \quad (13)$$

where X , X_{\max} , and X_{\min} are the values of the displacement or rotations variable and its corresponding maximum and minimum values.

The values of these various constants for the discs, ligaments, muscles and joints for the various directions and motion are difficult to specify precisely due to a lack of experimental data. However, the values for the discs may be obtained from Markolf and Steidal [21], Orne and Liu [1], and McKenzie and Williams [2]. The ligament and muscle attach points may be obtained from Francis [22], Lanier [23], and Todd and Lindala [24], with the spring and visco-elastic constants obtained from Nunley [25] and Close [26].

EQUATIONS OF MOTION

The model of Figure 1 can be considered as a "general chain system"--that is, a system of rigid bodies arbitrarily assembled such that no closed loops are formed. (Such systems are sometimes called "open-chains" or "open-trees".) Using Lagrange's form of d'Alembert's Principle as developed by Kane et al. [27-30], R. Huston and Passerello [31,32] have developed procedures and computer algorithms to study such systems. Indeed, they have shown that the equations of motion may be written in the form:

$$a_{ij} \ddot{x}_j = f_i \quad (i, j = 1, \dots, N) \quad (14)$$

where N is the number of degrees of freedom of the system, x_i are the generalized coordinates, and a_{ij} and f_i are, in general, functions of x_i and \dot{x}_i . (Regarding notation, unless otherwise specified, there is a sum over repeated indices over the range of that index).

For the system shown in Figure 1 the number of degrees of freedom is 54, and hence 54 generalized coordinates (27 translation and 27 rotation) need to be defined to describe the configuration of the system. It is convenient to define these coordinates as relative or local coordinates (i.e. between the respective bodies) as opposed to absolute or global coordinates (i.e. with respect to inertia space). Upon introducing these coordinates, the angular velocities relative to an inertia frame of the various bodies of the system may be written in the form:

$$\omega_k = \omega_{ijk} \dot{x}_j N_i \quad (i = 1, 2, 3; j = 1, \dots, 27; k = 1, \dots, 9) \quad (15)$$

where N_i are mutually perpendicular unit vectors fixed in an inertial reference frame R and where the ω_{ijk} are called "partial rates of change of orientation" [29] and are in general functions of x_i . Similarly, the velocities of the mass centers in R of the various bodies of the system may be written in the form:

$$v_k = v_{ijk} \dot{x}_j N_i \quad (i = 1, 2, 3; j = 1, \dots, 54; k = 1, \dots, 9) \quad (16)$$

where the v_{ijk} are called "partial rates of change of position" [29] and are in general functions of X_i . Lagrange's form of d'Alembert's principle then leads to governing equations of the form of Equations (14) with N equal to 54, and with a_{ij} and f_i given by the expressions:

$$a_{ij} = m_p v_{pjk} v_{pik} + I_{pkn} \omega_{pjn} \omega_{pik} \quad (17)$$

and

$$f_i = -(F_i + m_p v_{pik} \dot{v}_{pqk} \dot{X}_q + I_{pkn} \omega_{pin} \dot{\omega}_{pqk} \dot{X}_q + e_{nmk} \omega_{pqn} \omega_{psr} \omega_{pik} I_{pmr} \dot{X}_q \dot{X}_s) \quad (18)$$

where F_i represents the generalized force with respect to X_i and it may be expressed as [27]:

$$F_i = v_{pik} F_{pk} + \omega_{pik} M_{pk} \quad (19)$$

where F_{pk} and M_{pk} are the N_k components the equivalent centroidal force and torque of the equivalent couple acting on the p th body of the system.

Equations (14) then represent a system of 54 simultaneous, second order, ordinary differential equations. They may be integrated numerically using a standard integration scheme. Results of such an integration for a variety of specific cases are presented in the next part of the paper.

EXPERIMENTAL VERIFICATION

Several experiments have been conducted which may be used to obtain a validation of the model. In one of these, a seated cadaver was subjected to head impacts by a rigid pendulum. Accelerometers were used to measure the resultant frontal and occipital head impact forces and accelerations. Using the impact force data as input, the acceleration was calculated using the computer model. A comparison of the results for two of the frontal impact experiments, 6-2 and 6-5 is shown in Figures 2-5.

In the same set of experiments, high-speed cameras were used to measure the acceleration, velocity, and displacement of the mass center. A comparison of the results with those predicted by the computer model for experiments 6-1 and 6-2 are shown in Figure 6.

Finally, the model was checked against live human data generated by Ewing and Thomas [33] using elaborate testing facilities. A comparison of the results for the head angular acceleration, angular velocity, and angular displacement is shown in Figures 7, 8 and 9.

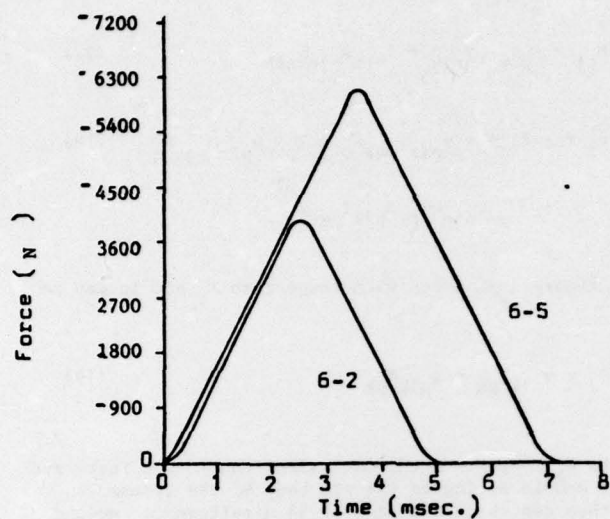


Fig. 2 Frontal impact force

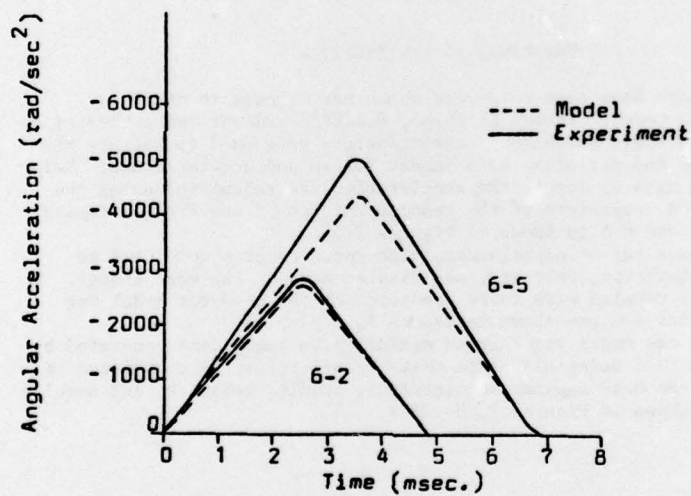


Fig. 3 Comparison of model and experiment for angular acceleration of the head

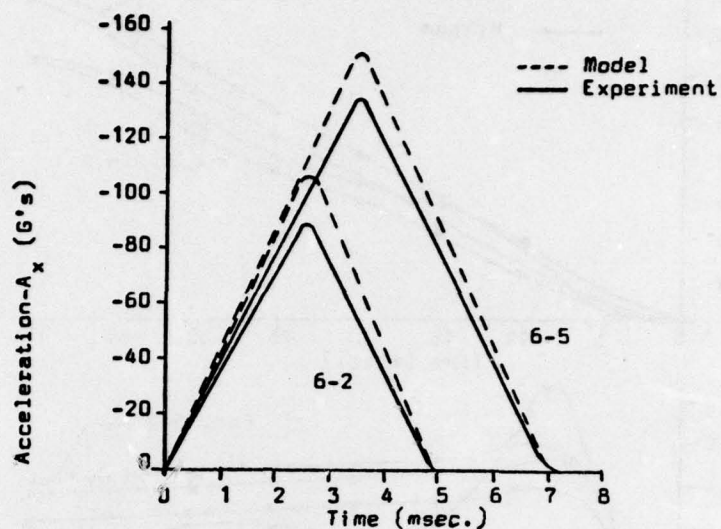


Fig. 4 Comparison of model and experiment for forward acceleration

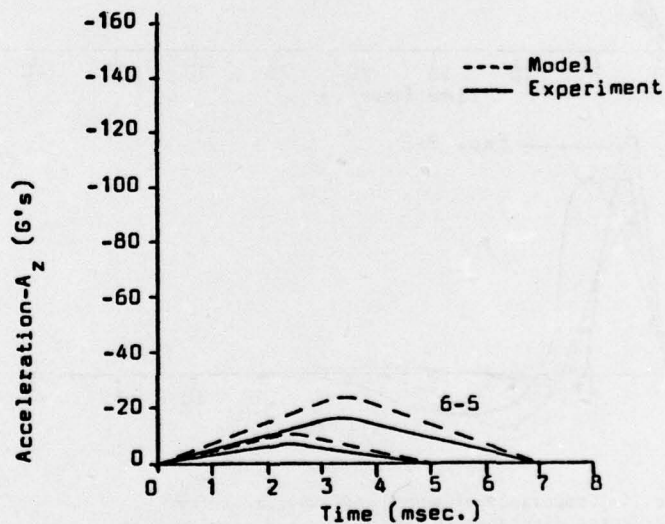


Fig. 5 Comparison of model and experiment for vertical acceleration

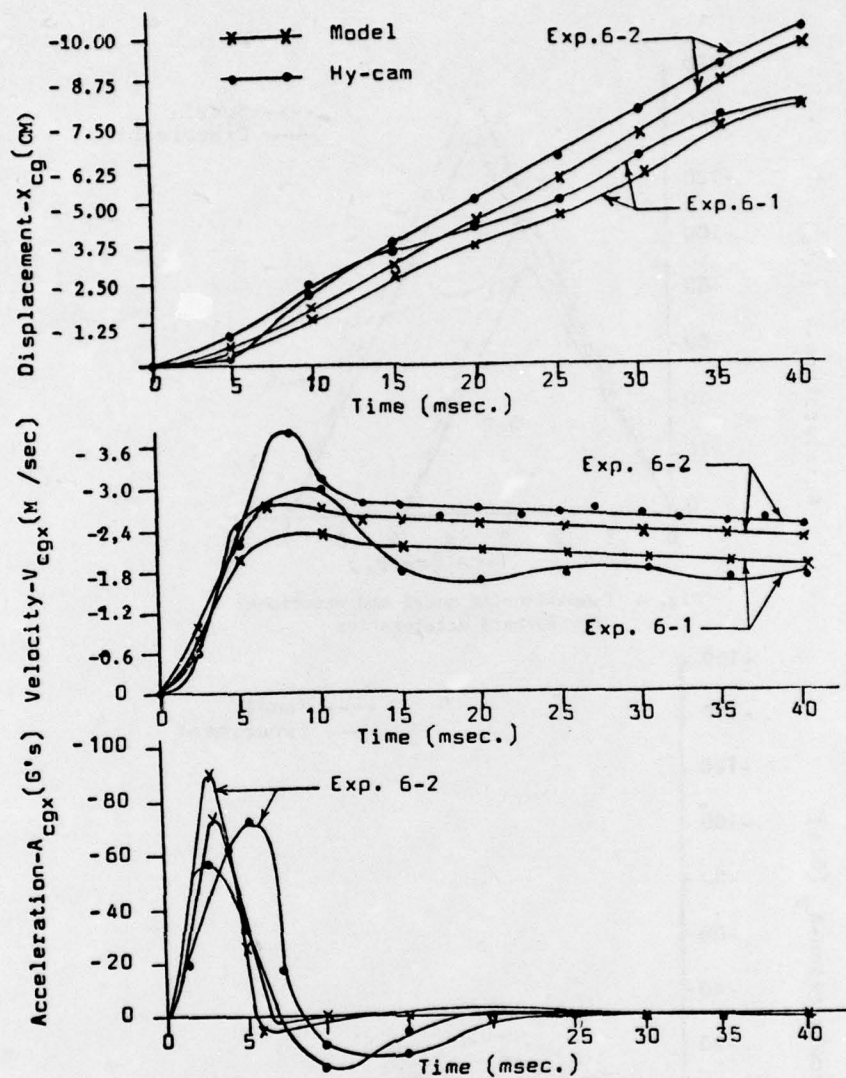


Fig. 6 Comparison of model and experiment for head mass-center displacement, velocity, and acceleration

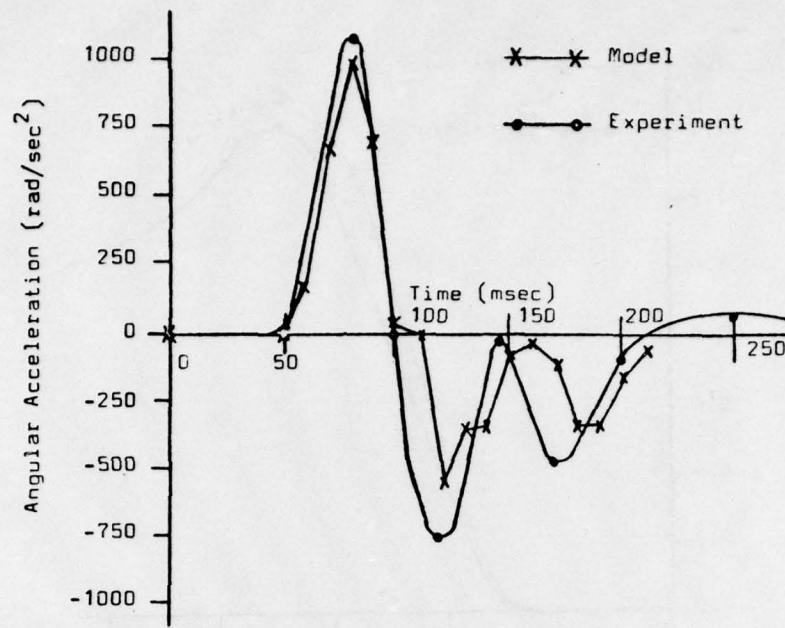


Fig. 7 Comparison of model and Ewing experiment for head angular acceleration

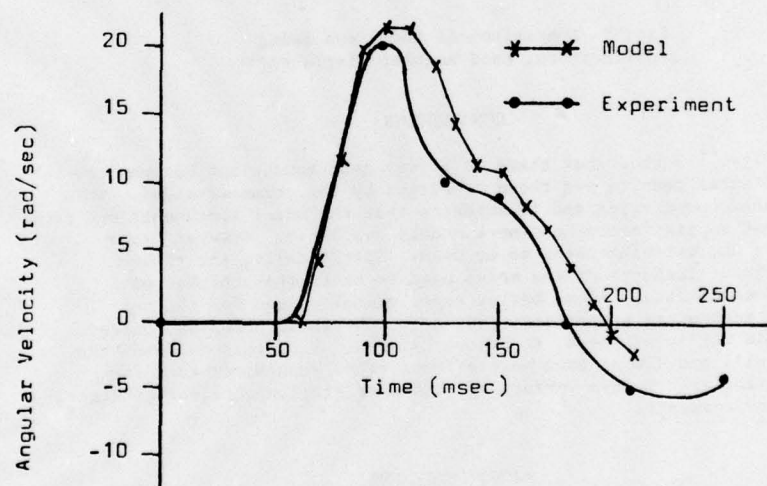


Fig. 8 Comparison of model and Ewing experiment for head angular velocity

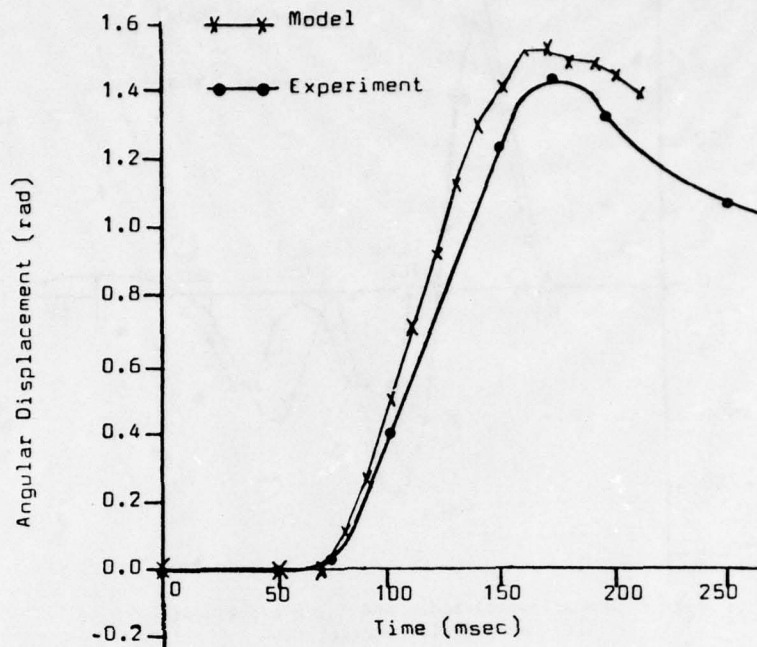


Fig. 9 Comparison of model and Ewing experiment for head angular displacement

CONCLUSIONS

Figs. 1-9 show that there is a very good comparison between the experimental results and those predicted by the computer model. This is indeed encouraging and it suggests that the model represents one of the most sophisticated head-neck models available. However, more testing and refining needs to be done. Specifically, the three-dimensional features of the model need to be further checked with experimental data. Also, better experimental values for the soft tissue mechanical properties needs to be obtained. Finally, better criteria for injury need to be established. When this is done, the model will provide an even more effective and economical tool for predicting injury in a variety of high-acceleration/accident-configuration environments.

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